Activity 13: Scale and Expansion of the Universe

Materials:

Measuring tape
4 objects to represent galaxies

Today we will look at the evidence that supports our model of an expanding universe. But first, let's talk more about the size of the universe at the largest scales we can observe.

Part 1: Scale of the Universe

STEP 1: Below is a list of 11 astronomical objects. Our goal in this Part is to put them in order from smallest to largest. Here is the list in no particular order:

Average Star (like our Sun)
Comet
The Universe
Galaxy
Cosmic Web
Solar System
Virgo Supercluster
Local Group
Laniakea Supercluster
Gas giant planet (like Jupiter)
Nebula

STEP 2: A **solar system** is collection of objects, including planets, comets, and asteroids, that are orbiting around one or more stars.

How many stars are in our solar system?

STEP 3: A **comet** is an icy object on a highly elliptical orbit that may or may not leave a tail of ice and dust behind it. Although the tails of comets can get quite long (as much as an AU), let's focus on the core of the comet, which can range in size from a few football fields across to a few miles across.

Look at the list of astronomical objects above and pick 3 that you think would fit inside of our solar system. List them below and rank them in order from smallest to largest.

(smallest) 1.

2.

3.

(largest) 4. Solar System

Next we will look at objects that can contain up to 200 stars and their associated solar systems.

STEP 4: As mentioned in a previous Activity, a nebula is a cloud of gas and dust inside which stars can form. On the next page is pictured the Orion Nebula which is, as we discussed before, a stellar nursery. This nebula is about 25 light years across. Measure the size of the photograph using a ruler. How many inches wide is the picture?

Since the Orion Nebula is 25 light years wide, how many light years are in each inch of the picture?

STEP 5: Current estimates of the size of our solar system put its diameter at around 1.6 light years. Draw a circle on the picture of Orion that shows the relative size of our solar system (i.e., your circle should have a diameter of about 1.6 light years).

STEP 6: A nebula can contain dozens of stars. Draw 11 more to-scale circles at random locations on the picture so that we have a scale drawing of a dozen stars and their associated solar systems inside of a nebula.

Review: <u>Road Trip Analogy</u>

On the first day of class, we discussed the size of the solar system using a road trip analogy. At terrestrial speeds that we're familiar with (say, traveling 80 mph on the highway), it would take us about 51 years to drive from the Sun to the closest planet, Mercury. That's without stopping for sleep, fuel, bathroom, or food: 51 years of 24/7 travel at 80 mph. To drive from the Sun to Saturn would take about 1270 years, and to drive from the Sun to Pluto would take about 5,200 years.

Therefore, it would take us roughly 10,000 years to cross the diameter of our solar system moving at highway speeds.

Figure 1: Orion Nebula

STEP 7: Now let's extend the road trip analogy (summarized in the box above). First, how far are solar systems spaced apart in our region of space? You've already drawn a visual of this in the Orion image above, but the Orion nebula is relatively densely packed compared to the region of space around our Solar System.

Suppose we shrank our solar system down to the size of a *grain of sand*. So we're taking something that would require 10,000 years to cross at highway speeds and shrinking it down to a grain of sand.

At that scale, the average distance between solar systems in our region of space is about 10 meters (33 feet). So, if the solar system were a grain of sand and the room you're in is a region of space surrounding the solar system, about how many solar systems (represented by grains of sand) would you find in the room?

With this visual in mind, notice that most of our region of space is empty. And recall that the solar system itself is almost entirely empty space.

STEP 8:

A **galaxy** is a collection of solar systems along with gas, dust, dark matter, and other hard-to-see objects (like black holes and brown dwarf stars).

Our solar system is just one of the *hundreds of billions* of solar systems in the Milky Way galaxy and the diameter of the Milky Way is about *120,000 light years*. It is hard to visualize the size of the Milky Way, but let's try!

Returning to the scale where our solar system is a grain of sand: At that scale the Milky Way would stretch from L.A. to N.Y.C.

> To summarize: At the scale where it would take us 10,000 years of highway travel to cross a grain of sand that represents our solar system, the Milky Way is the size of the continental U.S.

STEP 9: Now let's look beyond our own galaxy. As unimaginably big as our galaxy is, it is still just one of many.

The nearest large galaxy to us is a spiral galaxy called Andromeda. The diameter of Andromeda is about *220,000 light years* and, as you calculated in a previous Activity, it is located a distance of about ***2.5 million light years*** from us.

Returning to our analogy, if the solar system is a grain of sand and the Milky Way is the continental United States, then the Andromeda galaxy would be located about a fifth of the way from the Earth to the Moon.

And that's the *nearest* large spiral galaxy.

STEP 10:

A **galaxy cluster** is a group of neighboring galaxies that are bound together by their gravitational attraction. A galaxy cluster can contain hundreds of galaxies.

Our Milky Way belongs to a galaxy cluster that we call the **Local Group**. The Local Group includes the Milky Way, Small and Large Magellanic Clouds, Andromeda, and numerous other galaxies.

To see a map of our Local Group, open this URL:
https://i.stack.imgur.com/UsM0M.jpg

This map shows most of the 54 galaxies that make up our neighborhood.

Using what you know about the distance between our galaxy and the Andromeda galaxy, what is the scale of the Local Group? In other words, make a rough estimate of how many light years wide the map is.

For an alternate map of the Local Group, open this URL:
https://images.app.goo.gl/LauJCotjSRyKAXbM6

Passing through the center of the map is a plane that's aligned with the plane of our galaxy. For each galaxy, a vertical line shows the distance from the plane to the center of that galaxy.

This second map has distances marked. Does the distance from the Milky Way to the edge of the Local Group agree roughly with your estimate made from the previous image?

STEP 11: If we zoom out even farther, we see that the Local Group belongs to an even larger *cluster of galaxy clusters,* which we call a **supercluster**. The Local Group belongs to the Virgo Supercluster.

The **Virgo Supercluster** contains at least *100 galaxy clusters*, one of which is our Local Group of galaxies. Other clusters in Virgo include the Virgo Cluster, Ursa Major Groups, Draco Group, and M81 Group. (Confusingly, there is a Virgo Cluster inside the Virgo Supercluster).

To see a map of the Virgo Supercluster, open this URL:
http://www.atlasoftheuniverse.com/virgo.html

Using the map, estimate roughly the distance from our Local Group to the Virgo Cluster.

STEP 12: Since 2014 it has been suggested that the Virgo Supercluster is actually part of a *much larger* supercluster, which is called the Laniakea Supercluster.

The **Laniakea Supercluster** contains between *300 and 500 galaxy clusters* (including our Local Group), which adds up to a grand total of about 100,000 galaxies. It has a diameter of over 300 million light years.

For a map of the Laniakea Supercluster, open this URL:
https://tinyurl.com/atk43uw

This is an extremely high-res image and to get the full effect I recommend you zoom in until you can make out the individual galaxies. See if you can find the Milky Way and Andromeda galaxies! Warning: the size of the image is about 150 megabytes. For a quicker download you can use this lower resolution one: https://tinyurl.com/4wkhv4dv

> Aside: The center of the Laniakea Supercluster is called the **Great Attractor** and, although it is difficult to see because the disk of our own galaxy obscures our view, it is estimated that the Great Attractor contains an extremely large amount of matter (and is likely another galaxy supercluster that's larger than our own Virgo Supercluster) which forms the gravitational center of the Laniakea Supercluster.

STEP 13: In 1998 astronomers began conducting the Sloan Digital Sky Survey (SDSS), which uses a telescope to scan the entire sky and map out the positions of galaxies. The telescope produces about 200 gigabytes of data every night and it's been observing for 20 years. By finding the direction pointing to each galaxy and its distance from us a 3D map of galaxies has been constructed.

To date, the SDSS has mapped out the locations of 1.2 million galaxies besides our own.

To see an image of the galaxies mapped by the SDSS, open the following URL. And remember, *each dot* in the image represents a galaxy!

https://tinyurl.com/y8c55m9u

The image shown contains nearly 50,000 galaxies, which is *only about 3 percent* of the galaxies that the SDSS has mapped out. The width of this image is about *6 billion light years*.

STEP 14: Notice the galaxies are *not* just uniformly distributed in space. What word(s) could you use to describe the pattern of galaxy distribution that you see?

Astronomers have nicknamed this arrangement of galaxies the **cosmic web**. Computer simulations have successfully recreated this cosmic web by starting with the distribution of matter after the Big Bang.

STEP 15: Open the URL below and watch the first 60 seconds of the video to see a simulation of the first billion years of the universe. It begins right after the Big Bang with a mostly uniform (but not *perfectly* uniform!) distribution of gas and eventually clumps itself into the cosmic web. Note: the view of the simulation is rotating, so some of the "movement" that you see is actually just the changing perspective.

https://youtu.be/xfgDoExbu_Q

It is along these "filaments" in the cosmic web that we find galaxies and galaxy clusters.

The density in the simulation video is represented by a color scale where the brighter the color, the higher the density. Notice how the density of gas increases (brighter colors) while the amount of empty space (black) in the volume increases. What fundamental force is responsible for this change?

SQ1:
Returning to the list of objects at the beginning of this Part, put them in order of size from smallest to largest.

(smallest) 1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11. (largest)

Part 2: Hubble's Law

Next, we will discuss the observations that support the conclusion that the Universe is expanding. These observations were made by American astronomer **Edwin Hubble** (after whom the space telescope is named) and other astronomers in the 1920's.

To understand those observations, we will use the Doppler Effect. First, let's review the Doppler Effect for light by filling in the blanks for this SQ from the last Activity:

SQ2:

If a spectrum is observed that has the same ______________________________

as the spectrum of a known element but the spectral lines appear shifted, this

can be explained by the ____________________ Effect. If the spectral lines are

shifted toward the color _____________ then the source is moving

______________________ us. And if the spectral lines are shifted toward the

color ________________ then the source is moving ___________________ us.

STEP 1: Hubble made observations of numerous galaxies. Except for the galaxies nearest us (like Andromeda), he found that all galaxies had one thing in common: their spectra are redshifted.

What does this imply about the motion of distant galaxies?

STEP 2: Hubble also found that *no matter in what direction* he looked, the galaxies' spectra are redshifted. Therefore, what does this imply about the *apparent* "center" away from which the galaxies are moving?

STEP 3: Taking it a step further, Hubble also noticed a relationship between the distance to a galaxy and its redshift. The more distant a galaxy is from us, the greater its redshift, and therefore the greater the speed with which it is moving away from us. This is known as Hubble's Law and is summarized below:

> **Hubble's Law**: The speed with which a galaxy is moving away from us is *directly proportional* to the distance to the galaxy.

Suppose we've observed two galaxies that we'll call A and B.

If A is twice as far away as B, what does Hubble's Law imply about the speed with which A is moving away from us relative to the speed of B?

SQ3: Let's summarize these results below.

Distant galaxies are all (redshifted / blueshifted), implying that they are all moving ______________________ us. The distance to a galaxy and the speed with which it's moving away from us are ___________________ proportional. Therefore, a galaxy that is twice as far away as another galaxy is moving away _____________________ as fast. Since we see the same result in every direction, then the location away from which they are all moving appears to be _________________.

In the next Part, we will see how the above summary leads to the conclusion that our universe is expanding.

A Note on Scientific Terminology: A **law** is typically a rule of nature which appears to be accurate based on our observations but for which we may not have an explanation. A **theory** is a *group* of rules of nature that also have some supporting explanation for *why* they are true. Therefore, a theory (like the Theory of Relativity or the Theory of Evolution) is actually *more robust* than a law (in direct opposition to how these words are used in everyday language).

Hubble's Law is an example. When Hubble first made his observation it was deemed a law. But thanks to the work of Hubble and others, Hubble's Law is now explained within the framework of the *Big Bang Theory*.

Technical Aside: There are causes of redshift other than just the Doppler Effect, and today we know that the redshift of distant galaxies is due mostly to what astronomers call *cosmological redshift*, which is a redshift caused by the expansion of space itself. We won't address that distinction today.

Part 3: The Expanding Universe

The current model of our universe, the **Big Bang Model**, accounts for Hubble's Law as a consequence of the phenomenon that space is expanding like an elastic sheet. In this Part, we will see that a model of space expanding like an elastic sheet correctly reproduces Hubble's Law.

STEP 1: We will build a model in which we use 4 objects to represent 4 galaxies that are moving apart. The 4 objects could be anything: people, books, pencils, water bottles, etc.

We are going to look at the distribution of galaxies at three different times which we'll number Time 0, Time 1, and Time 2.

In our model universe, the galaxies are arranged in a straight line. In reality – as you saw in Part 1 – galaxies are distributed in three dimensions, not just one. But for our purposes, galaxies distributed along one dimension still illustrates the idea.

The four galaxies will be called *A*, *B*, *C*, and *D*.

STEP 2: We will arrange the galaxies *A* through *D* side by side in a straight line. *A* should be on one end, then *B*, then *C*, and *D* should be at the other end.

Choose an initial separation distance for the galaxies. We'll call this distance "X". If you're doing this with people for galaxies, I recommend X=1 meter (or 1 yard). If you're doing this with objects on a desk or on the floor, X=6 inches or 1 ft would work. Use a measuring tape to space the galaxies out evenly.

Your initial setup (which we're calling Time 0) should look as follows:

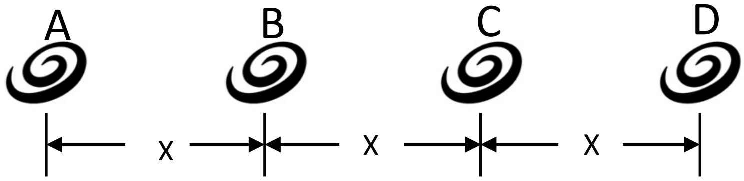

Figure 2: Time 0

where X is the initial separation distance you chose.

STEP 3: Using the measuring tape, measure the distance between B and C, the distance between B and D, and the distance between A and C. Record them in the table below in the rows for Time 0.

Time	**From B's Perspective**		**From C's Perspective**	
0	Distance to C		Distance to B	
	Distance to D		Distance to A	
1	Distance to C		Distance to B	
	Distance to D		Distance to A	
2	Distance to C		Distance to B	
	Distance to D		Distance to A	

Imagine for a second you live in galaxy B. You've already measured and recorded it, but now take a quick mental note of how far away galaxies C (your "first neighbor") and D (your "second neighbor") appear to be for someone living in galaxy B.

And do the same while imagining you live in galaxy C: take mental note of how far away galaxies B (your "first neighbor") and A (your "second neighbor") appear to be for someone living in galaxy C.

STEP 4: Our one-dimensional model universe is expanding. Spread out the four galaxies, A through D, until they are arranged in a line with 2X (i.e., double whatever the starting separation was) between each adjacent pair of galaxies.

Your arrangement should now look like this:

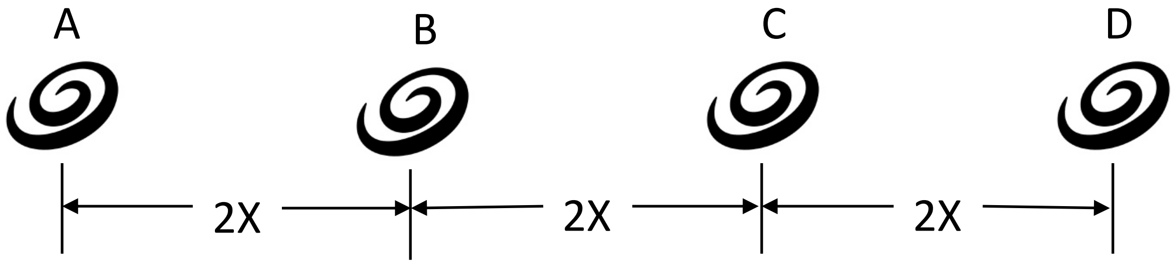

Figure 3: Time 1

Once again, imagine you live in galaxy B and take note of how far away your first neighbors are and how far away your second neighbor is. Did one of them appear to move more than the other since Time 0? If so, which one, your first neighbor or your second neighbor?

Now imagine you live in galaxy C. Did one of your neighbors appear to move more than the other since Time 0? If so, which one, your first neighbor or your second neighbor?

Use the measuring tape to measure the distances between galaxies as before and record them in the table above in the rows for Time 1.

STEP 5: The one-dimensional model universe expands some more. Spread out the four galaxies, A through D, until they are arranged in a line with 3X between each adjacent pair of galaxies.

Your arrangement should now look like this:

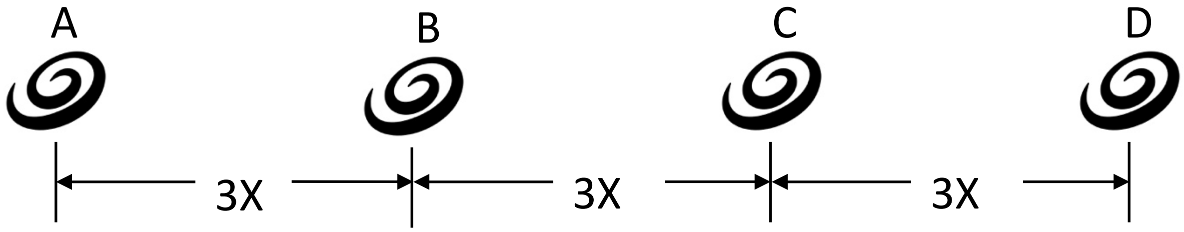

Figure 4: Time 2

One more time, imagine you live in galaxy B and look at your first and second neighbors. Has one of them appeared to move more than the other since Time 0? If so, which one?

And likewise, if you live in galaxy C, has either your first neighbor or second neighbor appeared to move more than the other since Time 0? If so, which one?

Use the measuring tape to measure and fill in the new distances in the table above.

That's all for collecting data. Now we will use the data you recorded in the table to answer the remaining questions.

STEP 6: Let's see whether our simple model of an expanding universe reproduces Hubble's Law.

From galaxy B's perspective, let's compute the *velocity* with which the other galaxies moved away from B. To find velocity we take the total change in distance and divide by the total change in time.

$$\text{velocity} = \frac{\text{Change in Distance}}{\text{Change in Time}}$$

In our case, we will compare the first time (Time 0) to the last time (Time 2). Let's find the velocity of C (as seen from B's perspective) by filling in the following table.

From B's Perspective:

Distance to C at Time 0	
Distance to C at Time 2	
Change in Distance to C from Time 0 to Time 2	
Change in Time from Time 0 to Time 2	
Velocity of C	

Now, let's repeat this process to find the velocity of D as seen from B.

From B's Perspective:

Distance to D at Time 0	
Distance to D at Time 2	
Change in Distance to D from Time 0 to Time 2	
Change in Time from Time 0 to Time 2	
Velocity of D	

SQ4: Use your above results to answer the following set of questions:

(a) How did the velocity of C (as seen by B) compare to the velocity of D (as seen by B)? What is the ratio of their velocities?

(b) At Time 0 how did the distance from B to C compare to the distance from B to D? What is the ratio of these distances?

(c) Looking back at (a) and (b), do these results agree with Hubble's Law? Why or why not?

STEP 7: Another observation made by Hubble was the fact that *all* galaxies appear to move away from *us*, making it seem as if we are at the center of the expansion.

However, since the days of Copernicus we've known that we are not at the center of our own solar system, much less the center of our galaxy, *much less* the center of the *entire universe*. Therefore, what we observe about the universe should not be special to us. Which means that *everyone* should see what we see: *all* galaxies are moving away from you, no matter which galaxy you live in.

Is this possible, for every point to move away from every other point so that each point appears to be at the center? Let's find out.

Look back at your table of distances (the first table) and look again at galaxy B. Did it experience the phenomenon that every other galaxy is moving farther away from it?

Now look at galaxy C in the table. Did it experience the phenomenon that every other galaxy is moving farther away from it?

Let's compute the velocities like we did before. This time, let's find the velocities with which B and A are moving *away from C* during the interval from Time 0 to Time 2 (i.e., 2 time units).

From C's Perspective:

Distance to B at Time 0	
Distance to B at Time 2	
Change in Distance to B from Time 0 to Time 2	
Change in Time from Time 0 to Time 2	
Velocity of B	

From C's Perspective:

Distance to A at Time 0	
Distance to A at Time 2	
Change in Distance to A from Time 0 to Time 2	
Change in Time from Time 0 to Time 2	
Velocity of A	

Do the observations taken from the perspective of galaxy C agree with Hubble's Law? Why or why not?

If D had enough neighbors on each side, would you expect someone in galaxy D would observe Hubble's Law as well? And would someone in D perceive every other galaxy as moving away from them?

SQ5: Let's imagine that there are many more galaxies along the one-dimensional line in our model universe. Now every galaxy has a first neighbor and a second neighbor (and a third, and so on). In this new larger model universe, do you expect each galaxy will observe Hubble's Law? What is your evidence from today's activity?

Now you can take a stab at answering this question: Where is the center of expansion of the Universe?

The expanding model that we've created just now is completely analogous to the way a one-dimensional rubber band stretches. In other words, points on a stretching rubber band obey Hubble's Law!

If we were to extend our one-dimensional model and make it infinitely long, and do that in all three dimensions (up/down, left/right, and front/back), then we have a good model of what our three-dimensional expanding universe looks like.

Additionally, the Big Bang Model accurately reproduces many other observations that we have (not just Hubble's Law), which is exactly what we demand from our models (aka *theories*) of nature.

FAQ about the Universe and the Big Bang

Q: Was the Big Bang an explosion?

A: No, not in the sense that we think of an explosion on Earth. Observations show us that the early Universe was very hot and very dense and that everything has been moving apart and cooling ever since. So we know that the Universe had a hot dense past. The term “Big Bang” was actually a derogatory name coined by the scientists that initially opposed the idea when it was first proposed. Those scientists advocated a “steady state” Universe that is neither expanding nor contracting, but observations have since ruled out that model and the expanding universe model has become the accepted model. Unfortunately, the derogatory name of “Big Bang” stuck.

Q: What caused or came before the Big Bang?

A: The short answer is: we don’t know. Some physicists argue that time was *created* at the Big Bang, so there can’t be a *before* since *before* is meaningless without the existence of time. Other physicists are working on models in which our Universe is part of a larger, higher-dimensional spacetime, in which the Big Bang may’ve been caused by a collision of objects in the higher-dimensional spacetime. In this model, there could be many Big Bangs besides ours, each creating its own Universe. This model has been dubbed the Multiverse.

Q: Where is the center of the Universe that everything is expanding away from?

A: As you may have concluded for yourself at the end of this Activity, there is no center or, equivalently, *every* point can be thought of as the center of the Universe’s expansion. So *you* are at the center of the Universe (but of course you already knew that, right?). Alternatively, if the Universe does exist inside a higher-dimensional space, then the center of our Universe’s expansion could be a point *outside* our own Universe.

Q: Does the Universe have an edge? Does it go on forever?

A: Again, we’re not sure. But, increasingly detailed measurements have pinned down two likely candidates for the geometry (actually “topology”) of the Universe. It appears likely that either (a) it goes on forever in every direction (and therefore is infinite), or (b) the Universe is finite and if you travel far enough in one direction you will eventually return to your starting point. Either way, the Universe has no edge. Additionally, the Big Bang model still works in either case.